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W-PAIR PRODUCTION WITH YFSWW/KORALW

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OUTLINE:

1. INTRODUCTION
2. WW PHYSICS WITH YFSWW/KORALW
3. RESULTS FOR σ_{WW}
4. CONCLUSIONS & OUTLOOK

PEOPLE:

S. JADACH, W.P., M. SKRZYPEK, B.F.L. WARD & Z. WĄS

PAPERS: (MOST IMPORTANT)

- KORALW: Comp. Phys. Commun. 94 (1996) 215;
  ibid. 119 (1999) 272
- YFSWW: Phys. Rev. D54 (1996) 5434;
  Phys. Lett. B417 (1998) 326;
  Phys. Rev. D61 (2000) 113010;
  hep-ph/0007012.

1. INTRODUCTION

→ EXPERIMENTALLY:

WW OBSERVED TROUGH 4f FINAL STATES
+ RADIATIVE PHOTONS

- GENERAL PROCESS:

$$e^+ + e^- \longrightarrow f_1 + \bar{f}_2 + f_3 + \bar{f}_4 + n\gamma \quad (n=0,1,\ldots)$$

→ THEORETICALLY: ALSO LOOP CORRECTIONS NECESSARY!

COMPLICATED

* ~200 CHANNELS (FINAL STATES)

* COMPLICATED PEAKING BEHAV. IN 8-DIM. PHASE SPACE

* LARGE NUMBER OF FEYNMAN DIAGRAMS

	# FEYNMAN GRAPHS/CHANNEL (WW-TYPE); $m_f=0$
BORN	9 ÷ 56
1-LOOP	3,579 ÷ 15,948

\+ TECHNICAL PROBLEMS – A FEW EXAMPLES:

- BORN → e.g. KORALW
  - SOURCE CODE: ~0.5M LINES → ~20M by
  - EXEC. CODE: ~10M by
  - COMPILATION TIME: ~1 HOUR ON FAST PC
- 1-LOOP: ROUGH ESTIMATE → MULTIPLY BY ~100
  - SOURCE CODE: ~50M LINES → ~2G by
  - EXEC. CODE: ~1G by
  - COMPILATION TIME: ~100 HOURS (IMAGINE DEBUGGING/TESTING!)

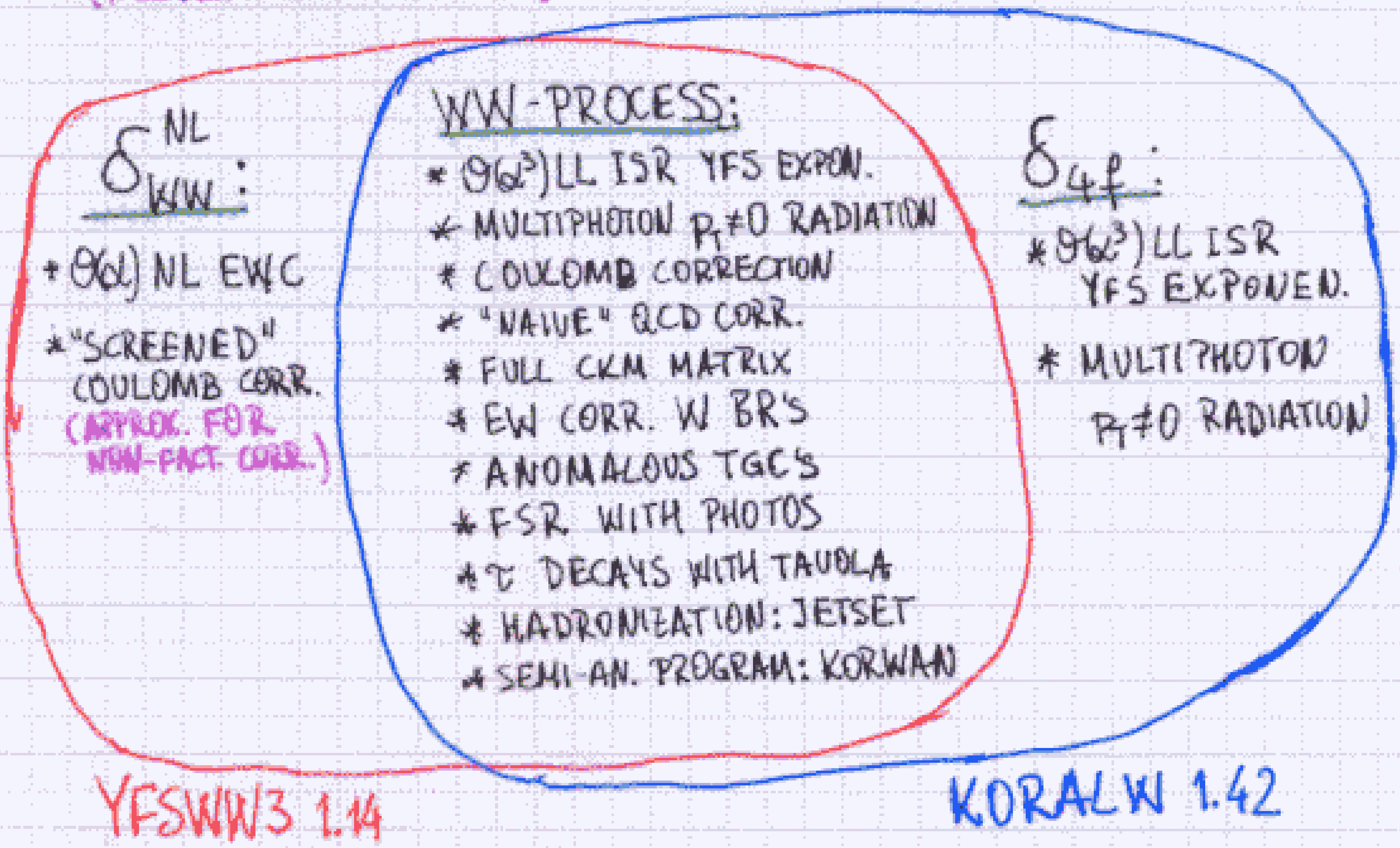
⇒ EFFICIENT APPROXIMATIONS NEEDED!

2. WW PHYSICS WITH YFSWW/KORALW

→ OUR SOLUTION:

TWO MC EVENT GENERATORS

↓	↓
YFSWW	**KORALW**
SIMPLIFIED PROCESS (DOUBE-RESONANT WW)	FULL PROCESS (ALL 4f CHANNELS)
⊕	⊕
AS MUCH RADIATIVE CORR. AS POSSIBLE (NEEDED FOR EXPER. PREC.)	SIMPLIFIED RADIATIVE CORR. (ISR, Coulomb, "trivial")



δ^{NL}_{WW}:

- $\mathcal{O}(\alpha)$ NL EWC
- "SCREENED" COULOMB CORR. (APPROX. FOR NON-FACT. CORR.)

WW-PROCESS:

- $\mathcal{O}(\alpha^3)$ LL ISR YFS EXPON.
- MULTIPHOTON $p_T \neq 0$ RADIATION
- COULOMB CORRECTION
- "NAIVE" QCD CORR.
- FULL CKM MATRIX
- EW CORR. W BR'S
- ANOMALOUS TGC'S
- FSR WITH PHOTOS
- τ DECAYS WITH TAUOLA
- HADRONIZATION: JETSET
- SEMI-AN. PROGRAM: KORWAN

δ_{4f}:

- $\mathcal{O}(\alpha^3)$ LL ISR YFS EXPONEN.
- MULTIPHOTON $p_T \neq 0$ RADIATION

YFSWW3 1.14

KORALW 1.42

⇒ TWO POSIBILITIES:

① $\sigma_{Y/K}$: Y ⊕ K ← RECOMMENDED FOR WW-PHYSICS

② $\sigma_{K/Y}$: Y ⊕ K ← RECOMMENDED FOR 4f WHERE $\delta_{4f} > \delta^{NL}_{WW}$

MORE DETAILS ...

- KORALW 1.42: ALL 4f FINAL STATES ($m_f \neq 0$)
  - 4f MATRIX ELEM. GENERATED BY PACKAGE GRACE (J. Fujimoto et al. MINAMI-TATEYA Collab.)
  - TWO INDEPENDENT PRESAMPLERS FOR FULL 4f PHASE SPACE
  - BOSE-EINSTEIN EFFECTS ACCORDING TO S. Jadach, K. Zalewski, Acta Phys. Polon. B28 (1997) 1363.
- YFSWW3 1.14: $\mathcal{O}(\alpha)$ EW CORRECTIONS IN W-PAIR PRODUCTION

→ LEADING POLE APPROXIMATION (LPA):

$$\underset{\substack{\uparrow\\ \text{MATRIX ELEMENT}}}{\mathcal{M}} = \sum_i \underbrace{T_i(\dots, p_j, \dots, p_k, \dots)}_{\substack{\text{SPINOR \& LORENTZ TENSOR}\\ \text{STRUCTURE OF MATR. EL.}\\ \text{(EXTERNAL WAVE FUNCTIONS, ...)}}} \underbrace{M_i(\dots, p_j \cdot p_k, \dots)}_{\substack{\text{LORENTZ SCALAR}\\ \text{FUNCTIONS}\\ \text{(FINITE-RANGE W-PROPAGATION, ...)}}}$$

→ TWO APPROACHES:

a) R. Stuart, Nucl. Phys B498 (1997) and refs. therein

M_i → EXPANDED ABOUT COMPLEX POLES (LAURENT SERIES) CORRESPONDING UNSTABLE PARTICLES

T_i – UNTOUCHED BY LAURENT EXPANSION!

→ LPA: ONLY LEADING-POLE TERMS KEPT

⇒ IMPLEMENTED IN YFSWW3 – CALLED $\boxed{\mathrm{LPA}_a}$ ← RECOMMENDED

b) YR CERN 96-01, Vol. 1, p. 79 and refs. therein

THE WHOLE MATRIX ELEM. $\mathcal{M}$ EXPANDED ABOUT POLES

→ LPA: ONLY LEADING-POLE TERMS KEPT

⇒ IMPLEMENTED IN YFSWW3 – CALLED $\boxed{\mathrm{LPA}_b}$ ← FOR TESTS, ...

BOTH GAUGE INVARIANT!

* NUMERICAL DIFFERENCES: $\mathrm{LPA}_a - \mathrm{LPA}_b$

Born	A FEW %	LPA_a CLOSER TO CC11
δ_{ISR}	A FEW ‰	
δ^{NL}_{EW}	$\lesssim$ 1‰	

→ FOR δ^{NL}_{EW} - NON-LL EW CORRECTIONS WE USE CALCULATIONS FOR ON-SHELL W-PAIR PRODUCTION:

- * J. FLEISCHER, F. JEGERLEHNER & M. ZRAŁEK, Z. PHYS. <u>C42</u> (1989) 409
  - → VIRTUAL CORRECTIONS
- * K. KOŁODZIEJ & M. ZRAŁEK, PHYS. REV. <u>D43</u> (1991) 3619
  - → HARD BREMESSTRAHLUNG

3. RESULTS FOR σ_{WW}

→ COMPARISONS WITH RACOONWW

RACOONWW - MC PROGRAM FOR WW-PHYSICS BY A. DENNER, S. DITTMAIER, M. ROTH, D. WACKEROTH, hep-ph/0006387.

- $\mathcal{O}(\alpha)$ VIRTUAL + SOFT RAD. CORR. IN DPA (INCLUDING NON-FACTORIZABLE)
- FULL $4f+\gamma$ MATRIX ELEMENT FOR $m_f=0$ (NON-COLLINEAR RAD.)
- $\mathcal{O}(\alpha^3)$ LL ISR WITH EXPONENTIATION

...

→ "WW-LINE SHAPE" (FROM WW-THRESHOLD TO 1.5 TeV)

→ SEE ALSO M. SKRZYPEK's TALK

YFSWW3 1.14 ⟷ RacoonWW

LEP2

$E_{CM} = 200$ GeV		σ_{WW} $[fb]$	
Final state	Program	Born	Best
$\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$	YFSWW3	219.770 (23)	199.995 (62)
	RacoonWW	219.836 (40)	199.551 (46)
	(Y−R)/Born	−0.03 (2)%	0.20 (4)%
$u\bar{d}\mu^- \bar{\nu}_\mu$	YFSWW3	659.64 (07)	622.71 (19)
	RacoonWW	659.51 (12)	621.06 (14)
	(Y−R)/Born	0.02 (2)%	0.25 (4)%
$u\bar{d}s\bar{c}$	YFSWW3	1978.18 (21)	1937.40 (61)
	RacoonWW	1978.53 (36)	1932.20 (44)
	(Y−R)/Born	−0.02 (2)%	0.26 (4)%

$\lesssim 0.3\%$

Table 1: The total WW cross sections from YFSWW3 and RacoonWW at $E_{CM} = 200\,GeV$ without cuts. The numbers in parentheses are statistical errors of the results corresponding to last digits.

LC

$E_{CM} = 500$ GeV		σ_{WW} $[fb]$	
Final state	Program	Born	Best
$\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$	YFSWW3	87.087 (11)	89.607 (32)
	RacoonWW	87.133 (23)	90.018 (27)
	(Y−R)/Born	−0.05 (3)%	−0.47 (5)%
$u\bar{d}\mu^- \bar{\nu}_\mu$	YFSWW3	261.377 (34)	279.086 (97)
	RacoonWW	261.400 (70)	280.149 (86)
	(Y−R)/Born	−0.01 (3)%	−0.41 (5)%
$u\bar{d}s\bar{c}$	YFSWW3	783.93 (11)	868.14 (31)
	RacoonWW	784.20 (21)	871.66 (27)
	(Y−R)/Born	−0.03 (3)%	−0.45 (5)%

$\lesssim 0.5\%$

Table 2: The total WW cross sections from YFSWW3 and RacoonWW at $E_{CM} = 500\,GeV$ without cuts. The numbers in parentheses are statistical errors of the results corresponding to last digits.

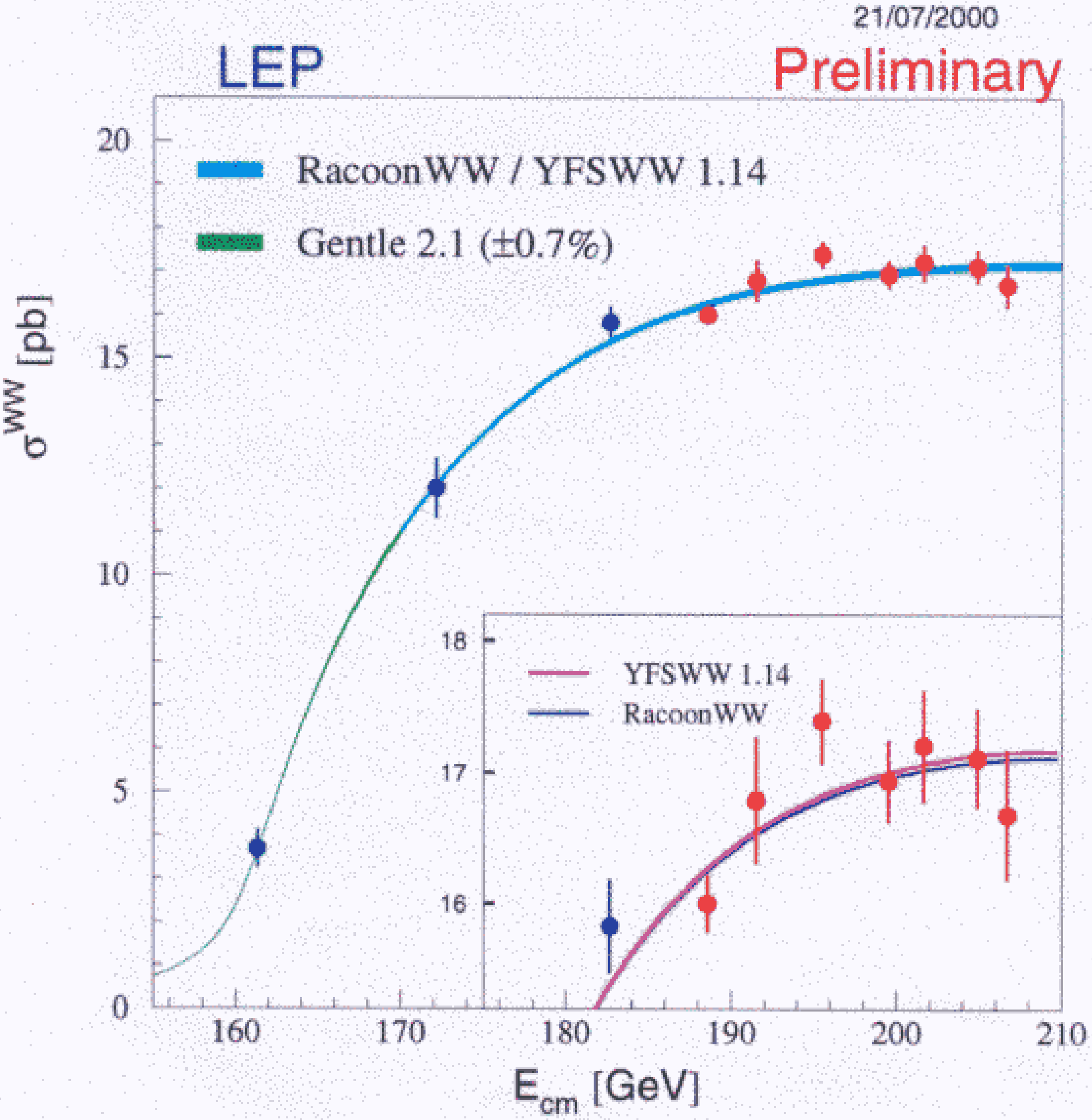
YFSWW3 1.14 $\longleftrightarrow$ RacoonWW

LEP2

$\sqrt{s}\,[GeV]$	σ_{WW} [pb]		(Y − R)/Y [%]
	YFSWW3	RacoonWW	
168.000	9.8302 (34)	9.8392 (49)	−0.09 (6)
172.086	12.0988 (41)	12.0896 (76)	0.08 (7)
176.000	13.6360 (45)	13.6271 (66)	0.07 (6)
180.000	14.7791 (49)	14.7585 (72)	0.14 (6)
182.655	15.3610 (50)	15.3684 (76)	−0.05 (6)
185.000	15.7755 (48)	15.7716 (78)	0.25 (6)
188.628	16.2664 (53)	16.2486 (111)	0.11 (8)
191.583	16.5680 (57)	16.5188 (85)	0.30 (6)
195.519	16.8409 (61)	16.8009 (87)	0.24 (6)
199.516	17.0167 (68)	16.9791 (88)	0.22 (6)
201.624	17.0755 (62)	17.0316 (89)	0.26 (6)
205.000	17.1279 (55)	17.0792 (89)	0.28 (6)
208.000	17.1507 (67)	17.0942 (90)	0.33 (7)
210.000	17.1467 (66)	17.0858 (91)	0.34 (7)
215.000	17.0786 (70)	17.0378 (91)	0.24 (7)

$\lesssim 0.35\%$

Table 1: The total WW cross section from YFSWW3 1.14 and RacoonWW at the LEP2 energy range (away from the WW threshold). The numbers in parentheses are statistical errors of the results corresponding to last digits.



▬ SPECIAL VERSION OF GENTLE (IBA-TYPE SAN PROGRAM)
TUNED TO RacoonWW/YFSWW3

"WW-LINE SHAPE"

YFS WW3: LPA_a

δ^{NL}_{EW} ↓

WW-THRESH. → 161.000

$\sqrt{s}\,[GeV]$	$\sigma^{tot}_{WW}\,[pb]$			$\frac{\text{ISR}-\text{Born}}{\text{Born}}$ [%]	$\frac{\text{Best}-\text{ISR}}{\text{Born}}$ [%]
	Born	ISR	Best		
155.000	0.94585 (17)	0.76497 (14)	0.75478 (35)	−19.12 (3)	−1.08 (5)
157.000	1.38578 (25)	1.10298 (19)	1.08686 (48)	−20.41 (3)	−1.16 (5)
159.000	2.30412 (40)	1.79141 (30)	1.76254 (80)	−22.25 (3)	−1.25 (5)
161.000	4.4138 (7)	3.3579 (5)	3.2969 (14)	−23.92 (3)	−1.38 (5)
163.000	7.3264 (10)	5.6178 (7)	5.5219 (22)	−23.32 (3)	−1.31 (4)
165.000	9.7343 (11)	7.6385 (9)	7.5073 (27)	−21.53 (3)	−1.35 (4)
167.000	11.5788 (14)	9.2903 (10)	9.1367 (31)	−19.76 (3)	−1.33 (4)
168.000	12.3391 (14)	10.0020 (11)	9.8302 (34)	−18.94(3)	−1.39 (4)
170.000	13.6124 (15)	11.2392 (12)	11.0504 (37)	−17.43 (3)	−1.39 (4)
172.086	14.6717 (16)	12.3114 (14)	12.0988 (41)	−16.09 (3)	−1.45 (4)
176.000	16.1293 (17)	13.8760 (15)	13.6360 (45)	−13.97 (3)	−1.49 (4)
180.000	17.1207 (18)	15.0325 (16)	14.7791 (49)	−12.20 (3)	−1.48 (4)
182.655	17.5852 (19)	15.6190 (17)	15.3610 (50)	−11.18 (3)	−1.47 (4)
185.000	17.8981 (19)	16.0422 (18)	15.7755 (48)	−10.37 (3)	−1.49 (4)
188.628	18.2391 (20)	16.5540 (18)	16.2664 (53)	−9.24 (3)	−1.58 (4)
191.583	18.4179 (20)	16.8649 (18)	16.5680 (57)	−8.43 (3)	−1.61 (4)
195.519	18.5466 (19)	17.1651 (19)	16.8409 (61)	−7.45 (3)	−1.75 (4)
199.516	18.5828 (19)	17.3608 (19)	17.0167 (68)	−6.58 (3)	−1.85 (4)
201.624	18.5696 (21)	17.4284 (19)	17.0755 (62)	−6.15 (3)	−1.90 (4)
205.000	18.5162 (21)	17.4968 (20)	17.1279 (55)	−5.51 (3)	−1.99 (4)
208.000	18.4399 (21)	17.5216 (20)	17.1507 (67)	−4.98 (3)	−2.01 (4)
210.000	18.3767 (21)	17.5219 (20)	17.1467 (66)	−4.65 (2)	−2.04 (4)
215.000	18.1833 (21)	17.4773 (20)	17.0786 (70)	−3.88 (2)	−2.19 (4)
250	16.2477 (16)	16.2293(14)	15.7952 (44)	−0.11 (2)	−2.67 (3)
350	11.3812 (12)	11.9325 (12)	11.5255 (39)	4.84 (2)	−3.58 (4)
500	7.3621 (8)	7.9823 (9)	7.6324 (30)	8.42 (2)	−4.75 (4)
750	4.2885 (6)	4.7993 (6)	4.5349 (21)	11.91 (2)	−6.17 (5)
1000	2.8598 (4)	3.2679 (4)	3.0543 (16)	14.27(2)	−7.47 (5)
1250	2.0714 (3)	2.4017 (4)	2.2263 (13)	15.95 (2)	−8.47 (6)
1500	1.5865 (2)	1.8615 (3)	1.7095 (11)	17.33 (2)	−9.58 (7)

Table 1: The total WW cross sections from YFSWW3 1.14 at the LEP2 and LC energies. The numbers in parentheses are statistical errors of the results corresponding to last digits.

LPA_a PRECISION NEAR THRESHOLD: ~1%

(MORE TESTS/CALCULATIONS NEEDED)

→ NON-FACTORIZABLE CORRECTIONS MAY BE IMPORTANT THERE!

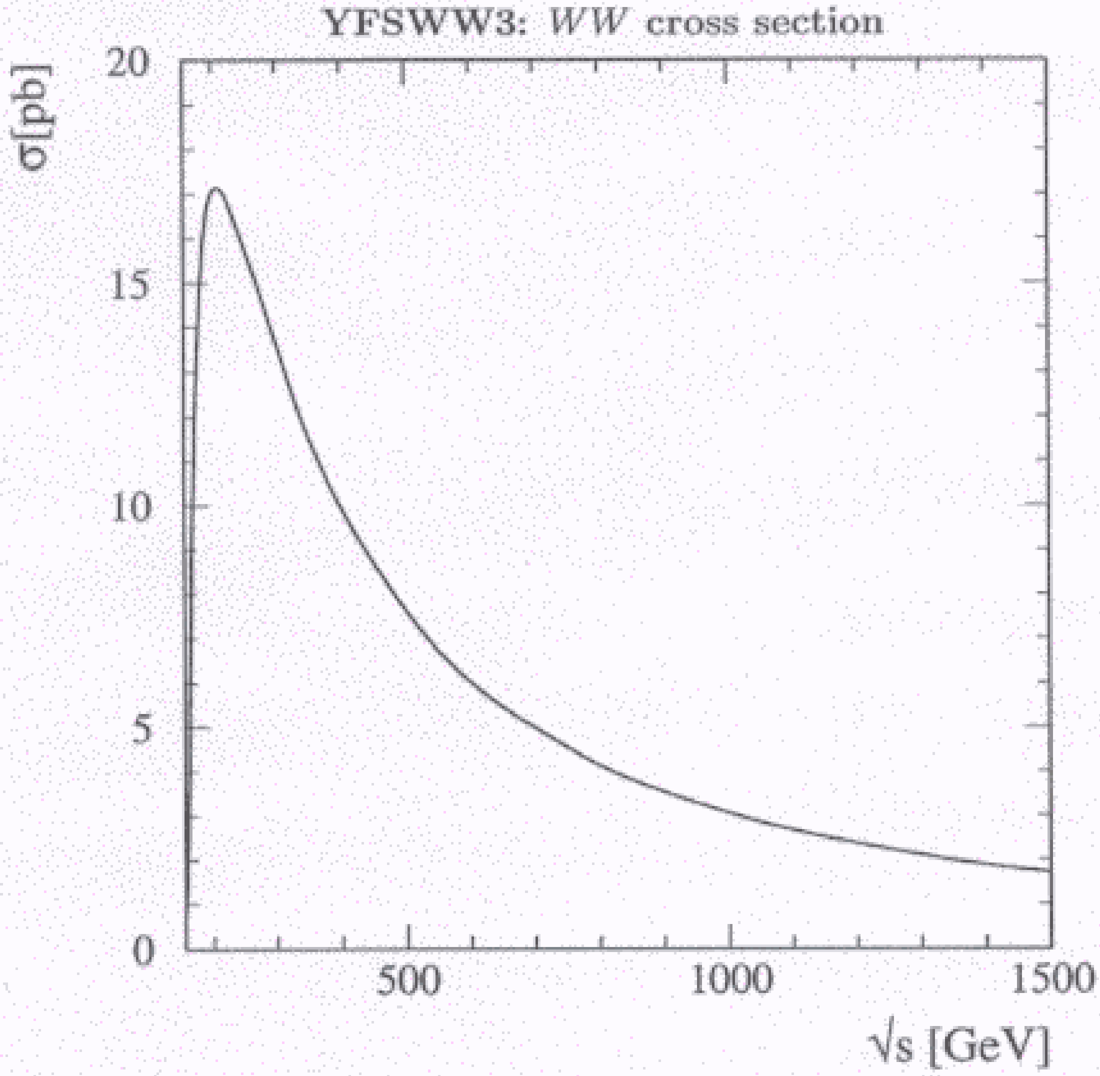


Figure 1: The total WW cross section from the MC event generator YFSWW3 1.14.

4. CONCLUSIONS ...

- OUR SOLUTION FOR WW-PHYSICS:

MC TANDEM

$\swarrow$ $\searrow$

YFSWW3 — WW-SIGNAL (HIGH PRECISION)

KORALW — 4f-BACKGROUND

- AGREEMENT: YFSWW3 – RacoonWW

$E_{CMS} = 168 \div 215$ GeV $\leqslant 0.35\%$

500 GeV $\leqslant 0.5\%$

CONSISTENT WITH LPA ACCURACY AT $\mathcal{O}(\alpha)$ ~0.5%

- $\mathcal{O}(\alpha)$ NON-LL EW RADIATIVE CORRECTIONS:

~ −1% ÷ ~ −2% AT LEP2 ENERGIES

~ −5% ÷ ~ −10% AT LC ENERGIES (0.5÷1.5 TeV)

(HIGHER ORDERS NEEDED!)

- ISR CORRECTIONS CHANGE FROM

LARGE NEGATIVE AT LEP2 ENERGIES

TO LARGE POSITIVE AT LC ENERGIES

$\Rightarrow$ PARTIAL CANCELLATION $\delta_{ISR} \leftrightarrow \delta_{EW}^{NL}$ AT LC ENERGIES

... OUTLOOK

- MULTIPHOTON RADIATION IN W-DECAYS
- EXPLICIT $\mathcal{O}(\alpha)$ EW CORRECTIONS IN W-DECAYS

} IN PROGRES

NOTE: SIMILAR SOLUTION FOR ZZ-PHYSICS: YFSZZ/KORALW

YFSZZ 1.02 – ONLY $\mathcal{O}(\alpha^2)$ LL ISR IN YFS SCHEME FOR ZZ

+ ANOMALOUS TGC's